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1977 H LASHINSKY AF-AFOSR-2179-72

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CONDUCTIVITY PROBE

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The program supported by this grant was devoted to extending theoretical and experimental techniques that are well-known in lumped-parameter systems such as vacuum tube oscillators and microwave devices to distributed-parameter systems such as plasmas; particular areas of interest are nonlinear behavior of oscillations and instabilities, stabilization of instabilities, and turbulence phenomena in bounded systems. The program developed a method of analysis in which the oscillations of a distributed-parameter system are treated in terms of normal modes of the bounded system. The temporal behavior of these modes is → next page

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described by nonlinear differential equations that are well known from the analysis of lumped-parameter systems: These include the van der Pol equation, the Mathieu equation, the Duffing equation, and a new equation that has been developed and solved in this program. An experimental program which used a low-temperature plasma device, the Q-machine, was used to provide verification of the above theoretical concepts by means laboratory experiments. This program has led to the development of a new (patented) oscilloscope display system, the development of so-called active microwave systems, and two new methods for plasma diagnostics: a Lecher wire system for the measurement of plasma density with high spatial resolution and a method for measuring anisotropic electrical conductivity in a plasma based on the measurement of the quality factor of a probe coil.

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UNIVERSITY OF MARYLAND

PRINCIPAL INVESTIGATOR: H. LASHINSKY

Nonlinear Mechanics of Unstable Plasmas As Related to High-Altitude Aerodynamics

FINAL REPORT

The program supported by this grant was devoted to extending theoretical and experimental techniques that are well-known in lumped-parameter systems such as vacuum tube oscillators, microwave devices, etc. to distributed-parameter systems such as plasmas; the results are also relevant to lasers, fluids, and gases. Particular areas of interest are nonlinear behavior of oscillations and instabilities, stabilization of instabilities, and turbulence phenomena in bounded systems.

The theoretical part of the program developed a method of analysis in which the oscillations of a distributed-parameter system are treated in terms of normal modes of the bounded system. The temporal behavior of these modes is described by nonlinear differential equations that are well known from the analysis of lumped-parameter systems: these include the van der Pol equation, the Mathieu equation, the Duffing equation, and a new equation that has been developed and solved in this program.

An experimental program which used a low-temperature plasma device, the Q-machine, was used to provide verification of the above theoretical concepts by means laboratory experiments. The experimental programs also led to the developments of several technological spinoffs and new in plasma diagnostic techniques.

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The general interest in the methods of analysis of nonlinear distributed-parameter systems developed in this program resulted in the solicitation of a monograph on this subject by the Principal Investigator. This monograph will provide scientists in various fields with the background needed to carry out similar work in their particular areas of interest.

Results obtained in the program include the following:

(1) Development and experimental verification of parametric excitation of ion acoustic waves in a plasma by means of a periodic temperature variation, which is produced by modulated radio-frequency power. (2) The application of this theory to determine the effect of initial phase in parametric excitation and the experimental observations of the predicted effects in a plasma. This effect had not been reported earlier. (3) A review and generalized analysis of dynamic stabilization methods. (4) The development and solution of a new nonlinear differential equation which describes the onset and saturation of a class of convection instabilities such as the Benard (thermal convection) instability. (5) The application of this equation to the analysis of the well-known plasma flute instability. The use of the new equation made it possible to examine certain ranges of parameters that could not be analyzed by the earlier approaches in the literature, which are based on the use of the dispersion relation. (6) An analysis of the entrainment effects in beam-plasma interactions based on the van der Pol model developed earlier in the program, experimental verification of this analysis. (7) The observations and explanation of a new plasma transparancy effect at high magnetic fields.

Recent unpublished results include (8) experimental demonstration of the suppression of the collisionless drift instability by the noncontact application of a tranverse radio-frequency field near the lower hybrid frequency. (9) The development and experimental verification of an analysis of the lower hybrid resonance in a bounded plasma. This analysis is based on the solution of the boundary-value problem whereas earlier treatments have been based on propagation in an infinite plasma.

This program has led to the development of certain technological spin-off developments. These include a new (patented) oscilloscope display system, the development of so-called active microwave systems, and two new methods for plasma diagnostics: a Lecher wire system for the measurement of plasma density with high spatial resolution and a method for measuring anaisotropic electrical conductivity in a plasma based on the measurement of the quality factor (Q) of a probe coil.

1 WAVE-INSTABILITY PHYSICS

1a) Parametric Excitation of Ion-Acoustic Waves

This work is of interest in connection with our general program designed to show that concepts well-known in lumped-parameter systems can be used to analyze the behavior of distributed-parameter systems such as a plasma in a magnetic field. The effect follows directly from the application of the Mathieu equation. The electron temperature in the plasma is controlled by the application of the rf power so that the electron temperature can be varied periodically by amplitude modulation of the rf power. In these experiments the temperature is modulated at a frequency equal to twice the frequency of the ion-acoustic wave. The usefulness of the method lies in the fact that it provides an additional means for excitation of ion-acoustic waves in the plasma; in turn these can be used to study the anomalous conductivity in the presence of a predetermined wave spectrum. The work on parametric excitation has been described in the Physics of Fluids, and at a recent international conference:

"Parametric Excitation of Ion-Acoustic Waves in a Bounded Plasma", by E. J. Yadlowsky, R. H. Abrams, Jr., T. Ohe and H. Lashinsky, Physics of Fluids, 14 1584 (1971).

"Excitation of Ion-Acoustic Waves by Parametric Heating and Strong High-Frequency Electric Fields", by R. H. Abrams, Jr., T. Ohe and H. Lashinsky, Proc. of 3rd International Conference on Quiescent Plasmas, Elsinore, Denmark, Danish Atomic Energy Commission, 1971, p. 79.

In this work it has been found that the electron temperature can be raised by the application of radio-frequency power, or by the application of microwave power and both techniques have been used. There are two independent experimental checks that show the temperature has increased: the frequency of the ion-acoustic wave increases with increasing rf power and rough probe characteristics, as can be obtained in the presence of the rf field, show decreasing slope with increasing rf power, indicating higher electron temperatures. The work on parametric excitation of ion-acoustic waves is described in a Ph.D thesis by Mr. T. Ohe, now being prepared, and in a paper to be submitted to the Physics of Fluids.

1b) RF Heating

In connection with the work on parametric excitation, it has been found that the application of radio-frequency power at very high levels, about one order of magnitude higher than those used in the parametric excitation experiments, leads to the excitation of ion-acoustic waves in the plasma without the use of the parametric excitation mechanism. There is also an accompanying increase in the electron temperature. The frequency at which the rf power is applied does not appear to have any influence on the observed effect. This behavior is to be contrasted with the conventional parametric excitation experiments in which power is applied at the electron plasma frequency. The observed phenomenon appears to be a new one and has not been reported earlier in the Western literature, although recent Soviet work seems to be related to it. It has been proposed that the mechanism responsible depends upon the excitation of electron plasma waves, which, in turn, couple to the ion-acoustic wave. The electron plasma waves are excited because the frequency of the applied radio-frequency power (10 MHz) is much lower than the electron plasma frequency (500-1500 MHz); on the time-scale of the electron plasma frequency the radio-frequency looks like a direct current. This direct current is then responsible for excitation of the two-stream instability. This work is related to computer-simulation experiments recently carried out at Princeton Plasma Physics Laboratory and reported in a paper entitled:

"Plasma Heating by Large-Amplitude, Low-Frequency Electric Fields", by Kruer, Katz, Byers and DeGroot, MATT 879, January 1972, Princeton Plasma Physics Laboratory.

The work in the present program is also described in two recently submitted papers:

"Plasma Heating in a High-Amplitude, Intermediate-Frequency Electric Field", R. H. Abrams, Jr., T. Ohe and H. Lashinsky, 1st Topical Conference on RF Plasma Heating, Texas Tech University, Lubbock, Texas, July 6-8, 1972.

"Plasma Phenomena in a Strong Intermediate-Frequency Electric Field", Fifth European Conference on Controlled Fusion and Plasma Physics, Grenoble, August, 1972, R. H. Abrams, Jr., T. Ohe and H. Lashinsky

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1c) Anomolous Resistance of a Collisionless Plasma

One of the topics of immediate interest in the controlled-fusion program is that of turbulent heating of collisionless plasmas. In plasmas of fusion interest the classical collisional mean-free path is longer than the dimensions of the system, so that heating must be accomplished by a non-classical or "anomalous" mechanism. If a plasma can be made turbulent by the generation of high-amplitude random waves, the scattering of the directed electron motion of these waves is analogous to the scattering of electron on ions in a solid and the transfer of momentum to the waves from the particles (the electrons) plays the role of a resistance. In the process the ions are heated. In the work carried out in this program over the past year we have been able to utilize a technique developed earlier that enables us to generate ion-acoustic turbulence in a plasma in a fairly controlled way. This technique is based on the rf heating mechanism described immediately above. In this work we are able to measure simultaneously the frequency spectrum of the turbulence, the time-autocorrelation function of the spectrum, and the Fourier transform of the autocorrelation function, i. e., the power spectrum. At the same time we are able to measure the voltage-current characteristics of the plasma column as a whole in the Q-machine, thus obtaining the plasma conductivity under various conditions of controlled turbulence. Although this work is still in a preliminary stage, it has been found that the anomolous resistivity is one or two orders of magnitude greater than the classical resistivity, as expected from theoretical considerations, and that the resistivity increases with the turbulence level. A preliminary report on this work has been given at the Madison meeting of the Plasma Physics Division of the American Physical Society:

"Low-Frequency Conductivity of a Collisionless Turbulent Plasma", R. H. Abrams, Jr., T. Ohe and H. Lashinsky, Bull. of American Physical Soc., Vol. 16, p. 1276, 1971.

1d) Nonlinear Saturation of Convection Instabilities

It can be shown that a number of problems involving convection-like phenomena such as the formation of Benard cells, the Rayleigh-Taylor instability in fluids, and various non-periodic plasma instabilities, such as the flute instability, give rise to an equation of the form

$$y'' + \alpha y' - ay = 0$$

when the problem is treated in the linear approximation. In work carried out in the past year we have shown that the description of nonlinear saturation of the convection process requires the introduction of a phenomenological cubic term with a positive coefficient to yield an equation of the form

$$y'' + \alpha y' - ay + by^3 = 0,$$

which provides saturation of the dependent variable when $y = (a/b)^{1/2}$. This procedure is analogous to the procedure used in introducing a phenomenological cubic nonlinearity in the dissipation term in the original derivation of the Van der Pol equation; in the present case the nonlinear saturation appears in the term that corresponds to the "restoring force" rather than the dissipation term. The physical origin of this term has been investigated and its significance in the various physical problems cited above has been determined.

In the mathematical analysis of the equation the parameter ranges for periodic and aperiodic solutions have been examined and related to the physical problems. Analytical solutions and computer solutions have been obtained for a number of cases of physical interest.

This work is described in a paper that has recently been accepted for an invitational international conference on nonlinear oscillations:

"On An Equation Related to Nonlinear Saturation of Convection Phenomena", Herbert Lashinsky and Ferdinand Cap, Sixth Internation Conference on Nonlinear Oscillations, Poznan, Poland, September, 1972.

Certain mathematical aspects of this work have been described in a paper stimulated by the present work:

"On Lashinsky's Equation $y'' + \alpha y' - ay + by^3 = 0$", Ferdinand S. Cap, Preprint X-641-71-481 Goddard Space Flight Center, December 1971.

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2 Q-MACHINE TECHNOLOGY

In the past year we have designed an improved shroud for the Q-machine. This shroud provides the function of trapping spent cesium and potasium and is water-cooled. The new shroud differs from the old one in that the access to the machine has been improved. The old shroud has been in use for some five years and has shown normal signs of deterioration due to continuous contact with the alkali metals.

3 GENERAL EXPERIMENTAL METHODS AND TECHNOLOGICAL SPINOFF

3a) Oscilloscope Display

A two-dimensional oscilloscope display has been developed in connection with plasma physics research carried out in this program. The device is used in two general applications:

1) Signal-to-noise enhancement by continuous signal averaging.

2) Data presentation in the form of an X-Y plot. In this application a conventional oscilloscope that presents a functional dependence of the form $y + y(t)$ is effectively converted into an X-Y plotter that presents a functional dependence of the form $y + y(t)$.

This display is also found to be highly convenient for the presentation of spectral data in compact form and also functions as an optical signal averager. In this application it is found to be extremely useful in plasma turbulence experiments and in the detection of signals whose frequencies are not known *a priori*. In the detection of drifting signals the present system seems to have certain advantages over conventional electronic signal averagers. A patent application was filed for this device by the Research Corporation, acting for the University of Maryland. It is expected that this device will provide a useful accessory for use in connection with oscilloscopes in various applications in science and engineering.

This device is described in a recent paper and a patent:

"Oscilloscope Display for Signal Averaging and X-Y Data Plotting", Review of Scientific Instruments, 42, pp. 1413-1418, October 1971 (H. Lashinsky and R. Monblatt).

U. S. Patent 3,609,540 "Raster Display Method and Apparatus", September 1971, H. Lashinsky and R. E. Monblatt.

3b) Active Microwave Systems

In the course of our plasma research a technique has been developed in connection with microwave diagnostics being used with the Q-machine. Although originally intended for plasma application, the new technique was found to exhibit features that may be of value in a number of problems of current scientific and technological interest. Conventional systems for the determination of the dielectric constant at microwave frequencies are "passive" in the sense that the quantities of interest are determined from a shift in phase or frequency in a passive element such as a microwave interferometer bridge or cavity resonator, the microwave energy required for the measurement being derived from an external source.

In contrast, the new approach makes use of an "active" system in which a positive feedback loop containing a microwave amplifier is used to provide gain. The entire configuration, including the measurement element, then comprises a microwave oscillator, the frequency and amplitude of the oscillator signal containing information on the quantities being measured. Experimental results obtained in plasma experiments indicate that the technique is attractive from the point of view of sensitivity, dynamic range, time-resolution and convenience of readout. It appears that the system can measure the real and imaginary parts of the dielectric constant of solids, liquids and gases at microwave frequencies with the capability of convenient transient measurements in the submicrosecond range as well as measurements in the presence of high losses which would be prohibitive for passive systems. This system would appear to be useful in process control in cases in which it is desired to monitor the dielectric constant or loss tangent, at microwave frequencies of any solid, gas, or fluid coming off a production line. The material being tested can move through the system on a continuous basis. The fact that the data can be read on a high-speed basis means that the information can be used to provide feedback to control various production processes.

There also appears to some application for a microwave refractometer capable of high time resolution in the study of clear air turbulence. Certain current experiments in clear air turbulence use an airborne microwave refractometer to sample localized fluctuations in the refractive index of the atmosphere. The aircraft carrying the microwave refractometer is simultaneously tracked by a high-resolution ground-based radar. The radar returns are then correlated with the localized readings of the fluctuations in refractive index of the atmosphere as obtained with the airborne refractometer. Conversations with people in the field have indicated that an active system might be capable of improving the available time resolution by an order of magnitude or more. A modest project is now being supported by the National Science Foundation to explore the use of this method in nonplasma applications. This work is funded by the Division of Engineering of the National Science Foundation.

3c) Microwave Plasma Diagnostics with Lecher-Wire Systems

Conventional systems used for plasma microwave diagnostics employ bounded resonant structures, such as cavity resonators, or non-resonant radiating structures, such as focused microwave horns. In either case, the spatial resolution that can be achieved in the measurement of plasma density is of the order of a wavelength of the microwave probing signal.

On the other hand, in many cases it is necessary to achieve high spatial resolution even though the electron density is so low that adequate sensitivity cannot be obtained with microwaves of short wavelength and high frequency. Moreover, when radiating structures are used inside the metal chambers characteristic of plasma laboratory experiments the measurements can be confused by spurious reflections from the metal walls.

It is possible to circumvent these problems by using wire conductors to guide the microwave probing radiation through plasma. In this case the microwave energy is carried by surface waves that propagate along the wires and the radiation field is confined to the immediate vicinity of the conductors so that high spatial resolution and freedom from spurious wall reflections can be realized.

Lecher-wire systems have been used for microwave diagnostics and are reported in the literature. A standard nonresonant microwave interferometer is generally used. The coupling is achieved by so-called finline sections. In the present work we have made use of a so-called single wire transmission line in conjunction with an active Fabry-Perot resonator, making use of the active microwave concept described above. The single-wire line has a number of interesting features as compared with the usual Lecher-Wire systems. There is much more flexibility in the choice of the wire diameter so that the diameter can be dictated by considerations of mechanical strength. In the Lecher-wire system the values of the diameter that satisfy requirements generally limit the mechanical strength. Moreover, it has been found possible to use a so-called flared-horn launcher with the single wire line. This type of transition section has a much higher efficiency than the tapered waveguide or finline and is also free from spurious radiation and spurious resonances. The results of this work have culiminated in the development of a diagnostic system which will be installed in the Q-machine. Also, this work on Lecher-wire systems has stimulated a great deal of development resulting in the installation of a Lecher-wire system in a laser-plasma experiment being carried out at the University of Maryland. This work was described at a recent conference:

"Active Single-Wire Fabry-Perot Interferometer for Microwave Plasma Diagnostics", Proceedings of 10th Internation Conference on Phenomena in Ionized Gases, Oxford, 1971 (R. C. Ajmera and H. Lashinsky).

I-4. Nonlinear Pulling Effects in Beam-Plasma Interactions

In connection with our work on general nonlinear models, earlier in this program we have studied an effect known as nonlinear entrainment. In the plasma case, this means that the application of a perturbation at a frequency close to the free-running frequency of an unstable plasma mode can cause the frequency of the unstable plasma mode to be "pulled" to the frequency of the incoming perturbation. It has been observed in beam-plasma interactions that the use of an unmodulated dc electron beam results in the production of a broad spectrum of plasma waves. On the other hand, if the electron beam is modulated at a frequency near the center of the broad spectrum all the wave energy appears at the frequency with which the electron beam is modulated. In other words, energy is taken out of other modes and transferred to the central frequency. This effect is predicted by the Van der Pol model developed in the present program. One practical application of this effect is in the study of the particle trapping in beam-plasma interactions. In these experiments it is desirable to create a monochromatic wave in order to eliminate a spurious effect associated with wave packets. It is found that the desired monochromatic wave can be obtained by the modulation scheme described above. The work in this area is described in a recent publication written together with a group from the Universi[illegible] of California at La Jolla:

"Van der Pol Model for Unstable Waves on a Beam-Plasma System" by Peter DeNeef and H. Lashinsky, Phys. Rev. Letters 31, 1039 (1973).

I-5. Nonlinear Saturation of Aperiodic Plasma Instabilities

A number of aperiodic plasma instabilities, such as the flute instability lead to the development of convection cells. Convection processes of this kind have been proposed by Kadomtsev as a mechanism for anomalous energy loss in toroidal plasma devices. It has been show[illegible] in the present program that in a bounded system a model equation that describes such instabilities is

$$\frac{d^2y}{dt^2} + \alpha\frac{dy}{dt} - ay = 0$$

when the problem is treated in the linear approximation. This equation describes the time growth of a typical quantity, say the convection velocity, at the outset of the convection process. It is evidently necessary to add some kind of appropriate nonlinear term to form an equation that can describe saturation and the steady-state conditions that are actually observed in physical experiments. On the basis of certain heuristic consideration we have then introduced a nonlinear term and examined the effect of this term on the properties of the equation and its solution. In turn, this nonlinear term can be relat[illegible] to an appropriate nonlinear physical effect. The modified equation is of the form

$$\frac{d^2y}{dt^2} + \alpha\frac{dy}{dt} - ay + by^3 = 0$$

This form is reached by analogy with the reasoning used in the derivation of the Van der Pol equation. The difference here is that the term capable of providing saturation is in the factor corresponding to the nonlinear restoring force, whereas the term that provides saturation in the Van der Pol equation is in the dissipation term. The form of the terms required in the nonlinear equation provides guidance as to the form of the orginal physical equation and to the modification of these equations which is required to obtain the appropriate nonlinear general equation. In other words, by knowing the final results should be in the model equation it is possible to choose the appropriate nonlinearities that must appear in the original physical equations. Procedures of this kind are useful in the study of instabilities in plasma physics in determining what physical mechanisms can provide the required saturation. Note that we have introduced the terminology "convection instabilities" here in order to avoid confusion with the term "convective instabilities" used in another application in plasma physics. This work is described in a recently published paper in a Polish journal on nonlinear oscillations:

"On an Equation Related to Nonlinear Saturation of Convection Phenomena," by F. Cap and H. Lashinsky, Nonlinear Vibration Problems (Warsaw), 14, 520 (1973).

In more recent work we have applied singular perturbation theory methods to examine the short-term and long-term behavior of the solution. We have also correlated results obtained by a multiple-time-scale formalism and singular perturbation theory. In particular, the role of secular terms has been delineated. A paper describing this more recent work is being prepared for submission to the Journal of Mathematical Physics.

I-6. Technological Spin-Off

In the course of plasma research in this program, a technique was developed for measuring density in the Q-machine. Although, originally intended for plasma applications, the new technique was found to exhibit features of value in a number of problems of current scientific and technological interest. The particular application presently being pursued is the use of this system in the determination of the size and dielectric constant of particles in the range 5-100 microns, a capability that appears to be useful in particulate measurements in pollution applications. This work on application of so-called "active" microwave systems is being carried out under a program which is entirely separate from the plasma program and which receives modest support from the Engineering Systems Division of the National Science Foundation. It is mentioned here inasmuch as it represents a spin-off from the plasma program. Interest in this device led to an invitation to submit a paper on this work, which appeared in a special issue of the Proceedings of the Institute of Electrical and Electronic Engineers:

"Microwave Measurements with Active Systems," by R. C. Ajmera, D. B. Batchelor, D. C. Moody and H. Lashinsky, Proceedings of Institute of Electrical and Electronics Engineers, 62, 118 (1974).

I-2. Measurement of Plasma Electrical Conductivity in a Strong Magnetic Field

During the past year, using a new technique, we have carried out measurements of the parallel and transverse components of the low-frequency electrical conductivity of a fully ionized plasma as defined in terms of parallel and perpendicular dissipation in moderate ($\omega_{ci}<\omega_{pi}$) and strong ($\omega_{ci}>\omega_{pi}$) magnetic fields (ω_{ci} = ion gyrofrequency; ω_{pi} = ion plasma frequency). These measurements are carried out by means of a noncontact method capable of simultaneous spatially localized measurements of the two components of the anisotropic electrical conductivity and appear to represent the first simultaneous determination of $\sigma_{\parallel}$ and $\sigma_{\perp}$ in a fully ionized plasma. These measurements derive from the measurement of electrical conductivity in terms of energy dissipation rather than momentum transfer, thus avoiding certain difficulties that arise when one attempts to define the transverse electrical conductivity of a plasma in a magnetic field in terms of momentum.

The plasma conductivity is determined by measuring the plasma-induced reduction in the quality factor (Q) of sensing coils arranged as shown in Fig. 1. The reduction in Q is measured with a sensitive Q-meter (Hewlett Packard 4342A) or by incorporating the coils into marginal oscillators in accordance with standard techniques used in nuclear magnetic

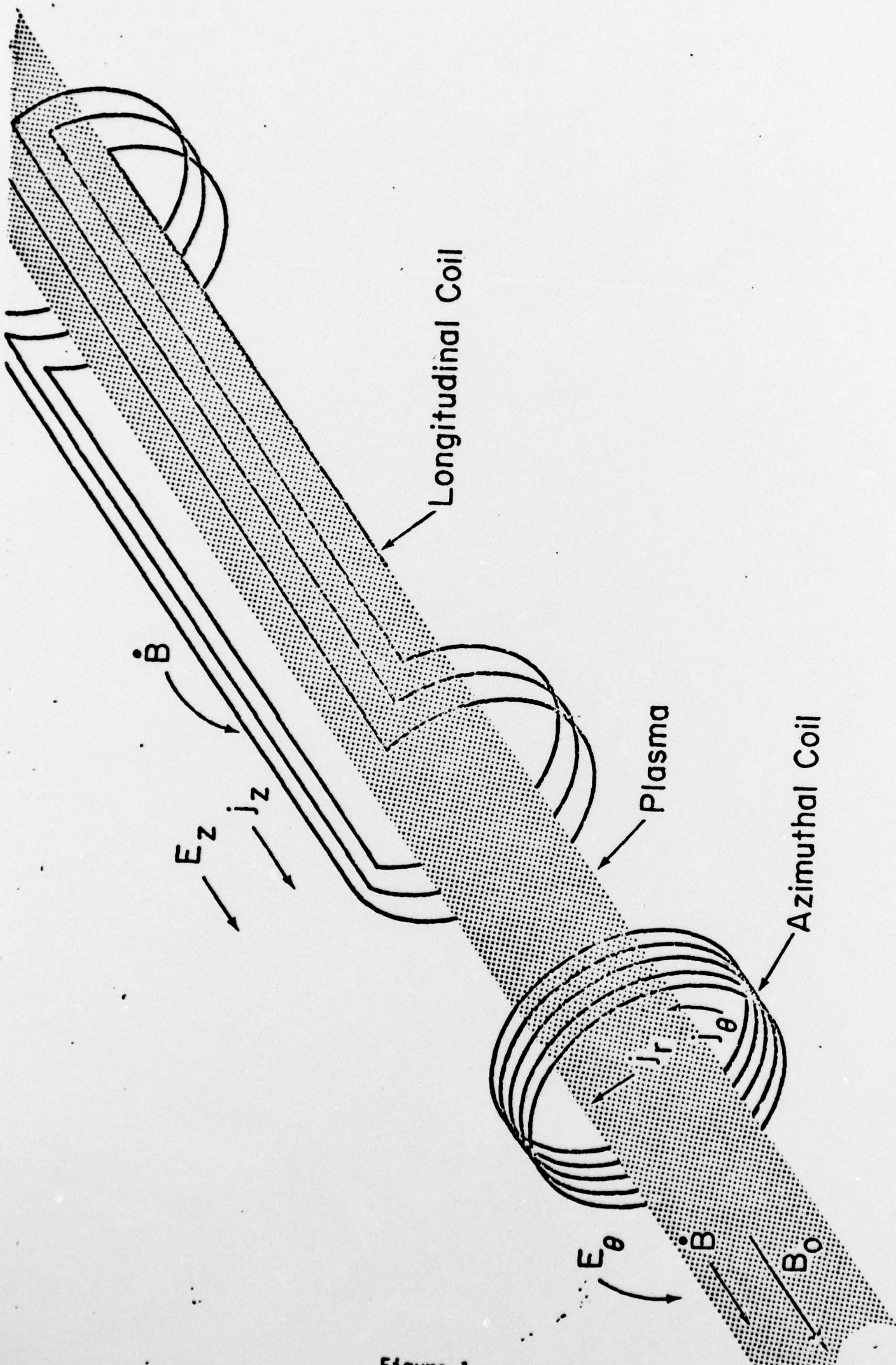
Longitudinal Coil
Plasma
Azimuthal Coil
$\dot{B}$
E_z
j_z
j_r
j_θ
E_θ
$\dot{B}$
B_o

Figure 1

resonance work. In either case the system is capable of absolute calibration with HCl solutions. It is interesting to note that this instrument has been found experimentally capable of a sensitivity of 5 micromhos per meter; this exceeds by perhaps two orders of magnitude the sensitivity of related devices reported in the literature.

Using the system described above, during the past year we have observed that the longitudinal electrical conductivity drops dramatically when the magnetic field increases so that the ion Larmor radius becomes smaller than the Debye length ($\omega_{ci} > \omega_{pi}$). At the present time the mechanism responsible for this effect is not known and relevant theory is not available in the literature. A note describing this new result is being submitted to Physical Review Letters and a preprint accompanies the present proposal. A note that describes the new radio-frequency conductivity meter is being submitted to the Review of Scientific Instruments.

Work on the measurement of plasma conductivity in quiescent and turbulent plasmas is described in the following papers:

"Anomalous Resistivity Due to Intermediate Frequency Fields," by J. R. Conrad, R. Gore, and H. Lashinsky, Proceedings of the 2nd Topical Conference on RF Plasma Heating, Lubbock, Texas, June 1974.

"Radio-Frequency Method for Plasma Conductivity Measurements," by R. Gore, J. R. Conrad, and H. Lashinsky, Bull. Am. Phys. Soc., Vol. 19, 911 (1974).

"Anomalous Resistivity in a Q-Machine Plasma," by J. R. Conrad, R. Gore, and H. Lashinsky, Bull. Am. Phys. Soc., Vol. 19, 955 (1974).

I-2. Plasma Transparency Effect in Strong Magnetic Fields

During the past year, to test a new method that will be used for other purposes, we have carried out measurements of the parallel and transverse components of the low-frequency electrical conductivity of a fully ionized plasma as defined in terms of parallel and perpendicular dissipation in moderate ($\omega_{ci}<\omega_{pi}$) and strong ($\omega_{ci}>\omega_{pi}$) magnetic fields (ω_{ci}= ion gyrofrequency; ω_{pi}=ion plasma frequency). These measurements are carried out by means of a noncontact method capable of simultaneous spatially localized measurements of the two components of the anisotropic electrical conductivity and appear to represent the first simultaneous determination of $\sigma_{\parallel}$ and $\sigma_{\perp}$ in a fully ionized plasma. These measurements derive from the measurement of electrical conductivity in terms of energy dissipation rather than momentum transfer, thus avoiding certain difficulties that arise when one attempts to define the transverse electrical conductivity of a plasma in a magnetic field in terms of momentum.

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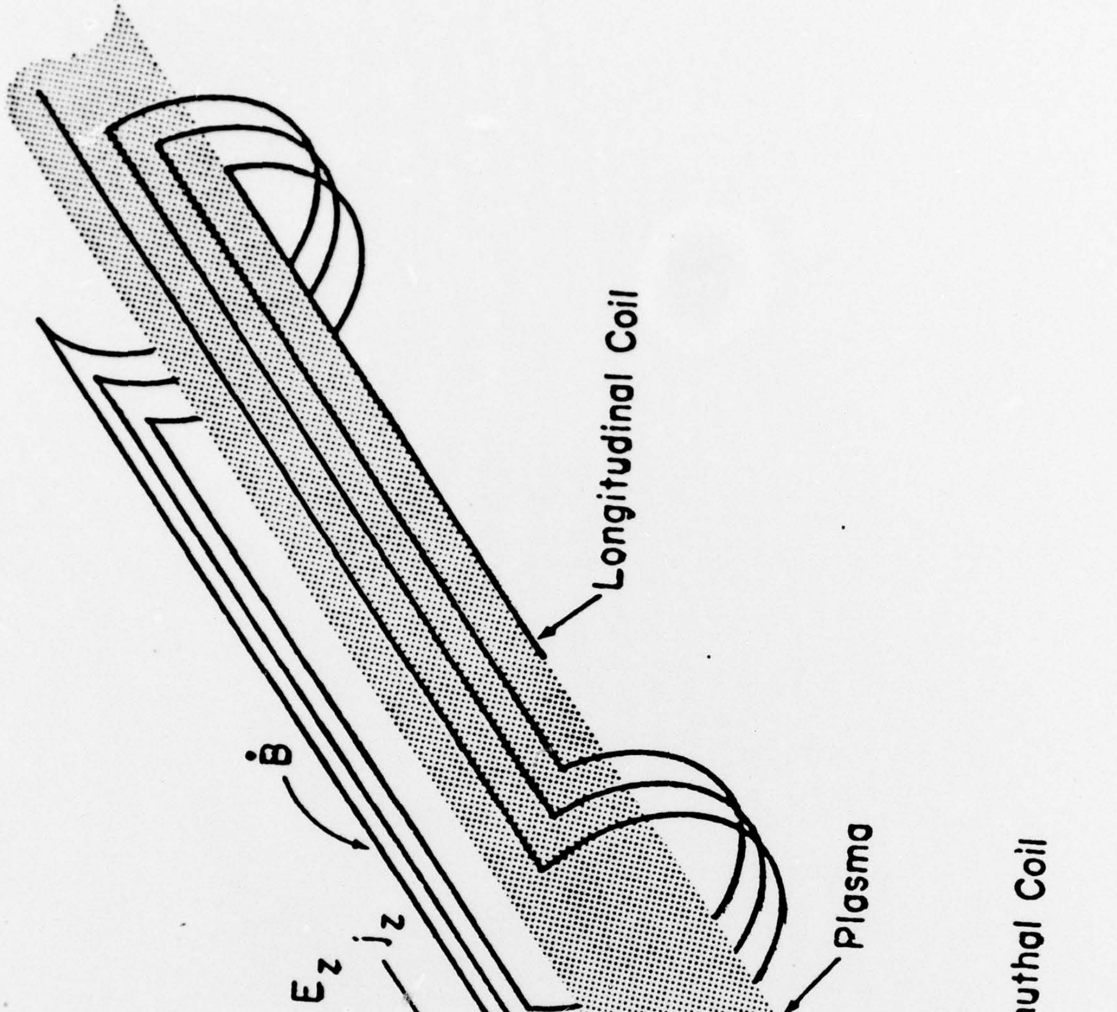

CONRAD et al

Figure 1

resonance work. In either case the system is capable of absolute calibration with HCL solutions. It is interesting to note that this instrument has been found experimentally capable of a sensitivity of 5 micromhos per meter; this exceeds by perhaps two orders of magnitude the sensitivity of related devices reported in the literature.

Using the system described above, during the past year we have observed that the transverse electrical conductivity drops dramatically when the magnetic field increases so that the ion gyrofrequency becomes larger than the ion plasma frequency ($\omega_{ci} > \omega_{pi}$). A theory is being developed to explain this effect; the fact that the plasma can not absorb transverse electromagnetic waves when $\omega_{ci} > \omega_{pi}$ appears to follow from the behavior of the plasma dispersion relation when this condition is satisfied. In Fig. 2a we show the pertinent dispersion relation for $\omega_{ci} < \omega_{pi}$ and it will be observed that there are large intervals in frequency in which the plasma is opaque (cross-hatched regions). On the other hand, when $\omega_{ci} > \omega_{pi}$ the diagram shown in Fig. 2a is transformed to that of Fig. 2b. Straightforward calculations show that the opaque regions now shrink to narrow bands around the electron and ion gyrofrequencies. The effect arises physically because the electrons and ions are "tied" so tightly to the field lines that they can not couple to transverse electromagnetic waves. Hence the wave propagates through the plasma as though it were transparent. Possible implications of this effect are discussed in Sec. II-2 or the renewal proposal and a paper describing this effect will be prepared in the near future. The preliminary work on this effect has been described in a talk:

"Plasma Conductivity Measurements in Large Magnetic Fields," by H. Lashinsky, J. R. Conrad and R. Gore, Proc. IEEE International Conference on Plasma Science, 1975. p. 34.

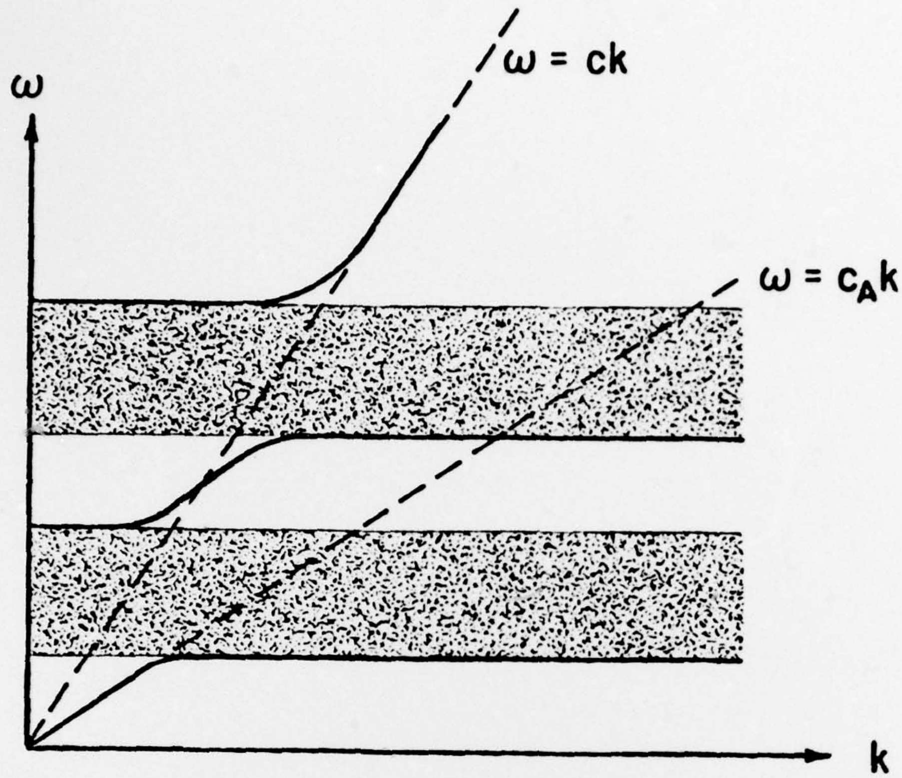

Figure 2a

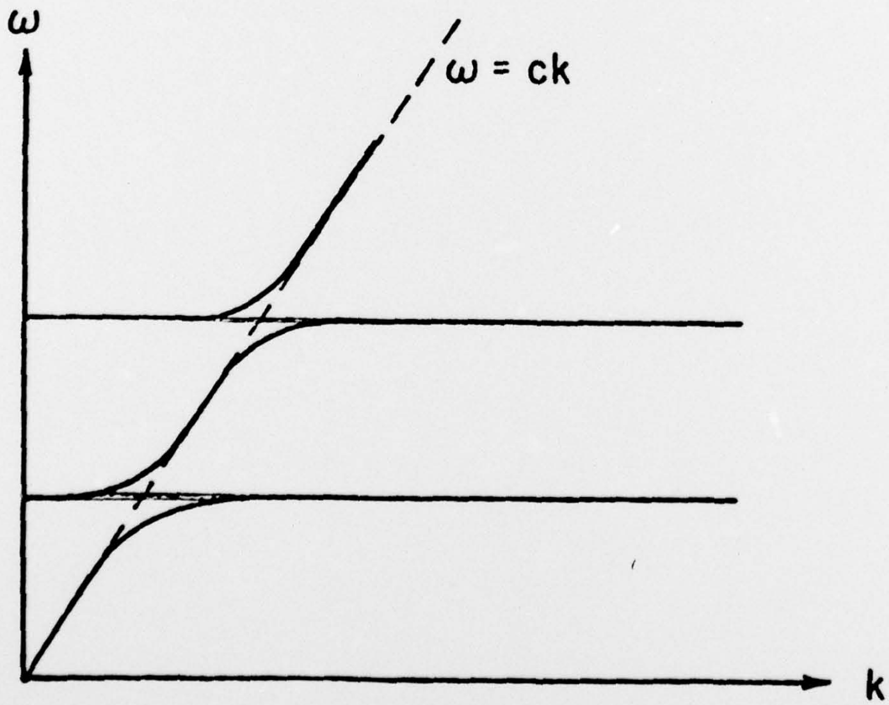

Figure 2b

I-3. Lower Hybrid Resonance in a Bounded Plasma

The conductivity-measurement system described above in I-2 has been found to offer a highly sensitive means for the measurement of a plasma resonance known as the lower hybrid resonance. This resonance is of great current interest in plasma work since it is regarded as a means of heating plasmas in controlled fusion. The lower hybrid resonance has also been found to play a role in certain antenna and propagation effects that have been observed in radio-frequency transmission from satellites.

In contrast with earlier work in the field, which has been concerned with the lower hybrid resonance in infinite plasmas, in the present experiments it has been found possible to measure lower hybrid "body" resonances, which accounts for the fact that the resonance occurs in a plasma of finite dimensions, so that the problem must be treated as a boundary-value problem. Physical effects in the bounded case, especially effects associated with coupling efficiency, are found to be modified in a significant way when the finite size of the plasma is taken into account and it is anticipated that the present results may be important in several applications of the lower-hybrid resonance. All of the important basic experimental features of the lower-hybrid body resonance have been verified and a paper on this work is in preparation.

I-4. Prototype Nonlinear Equation for Convection Instabilities

In the 1974-75 Progress Review we have reported on the analytic solution, by singular perturbation theory and multiple-time-scale methods, of an equation that describes the nonlinear saturation of convection instabilities such as the Rayleigh-Taylor instability in liquids and gases.

This equation was developed on a phenomenological basis and describes the nonlinear saturation of this class of aperiodic instabilities.

An interesting new feature is the result that the growth of the instability must be treated in two stages, an initial transient stage and the long term. The first stage, for short times, is then matched to the long-time solution. It is found that the time behavior of the solution for long times is the same as the envelope for the solution of the van der Pol equation, which describes the growth of most periodic instabilities. This new equation, which is a kind of counterpart for the van der Pol equation, should be of great utility since it is a generic equation that describes the time development of a large family of nonperiodic instabilities and can provide insight into the saturation behavior of these instabilities. A number of these instabilities are encountered in problems of hypersonic flow of plasmas and gases such as unstable Couette flow, various forms of the Kelvin-Helmholtz instability, and the Rayleigh-Taylor instability.

During the past year this equation has been applied to the description of a well-known plasma instability, the so-called flute instability, and has made it possible to analyze the nonlinear evolution of this instability, which has not been done as yet in the literature. By making use of this equation rather than the conventional dispersion relation, it has also been possible to extend the range of growth rates that can be analyzed. A preliminary report on this was given at the meeting of the Plasma Physics Division of the American Physical Society in November, 1975:

Convection Instability in a Weakly Ionized Plasma Confined by a Nonuniform Magnetic Field, by H. Lashinsky, P. Ottinger and J. Guillory. Bull. American Physical Soc. 20, 1363 (1975).

A detailed work paper on this work is being prepared for submission to the Physics of Fluids.

This equation has also been applied to the description of the well-known Benard instability, which describes the onset of thermal convection and this work is described in a recent talk:

Prototype Nonlinear Differential Equation for Fluid Convection Instabilities by R. Gore and H. Lashinsky. Bull. American Physical Society 20, 1418 (1975).

A detailed paper on this work was submitted to the Journal of Mathematical Physics, but after consultation with the editor it has been decided to submit it to the Physical Review, Series A, which was deemed more appropriate for its content.

I-5. Parametric Excitation

As reported in the Progress Review for 1974-75, a paper describing work carried on in this program on the parametric excitation of ion acoustic waves in a plasma has been accepted by the Physics of Fluids pending certain revisions. These revisions have been made and the paper is in press:

Parametric Excitation of Ion Acoustic Waves in a Fully Ionized Bounded Plasma by T. Ohe, R. H. Abrams Jr., and H. Lashinsky (Phys. Fluids, to appear).

In this paper we have shown the effect of initial phase on the parametric instability in a plasma. This is the first experimental demonstration of this effect in a plasma; however, the effect has implication for any system in which parametric excitation is used and the general applications of this phenomenon have been described at an invitational conference on nonlinear mechanics:

"Effect of Initial Phase on Nonlinear Parametric Excitation" by T. Ohe and H. Lashinsky, Proceedings of the 7th International Conference on Nonlinear Oscillations, Berlin, DDR 1975.
